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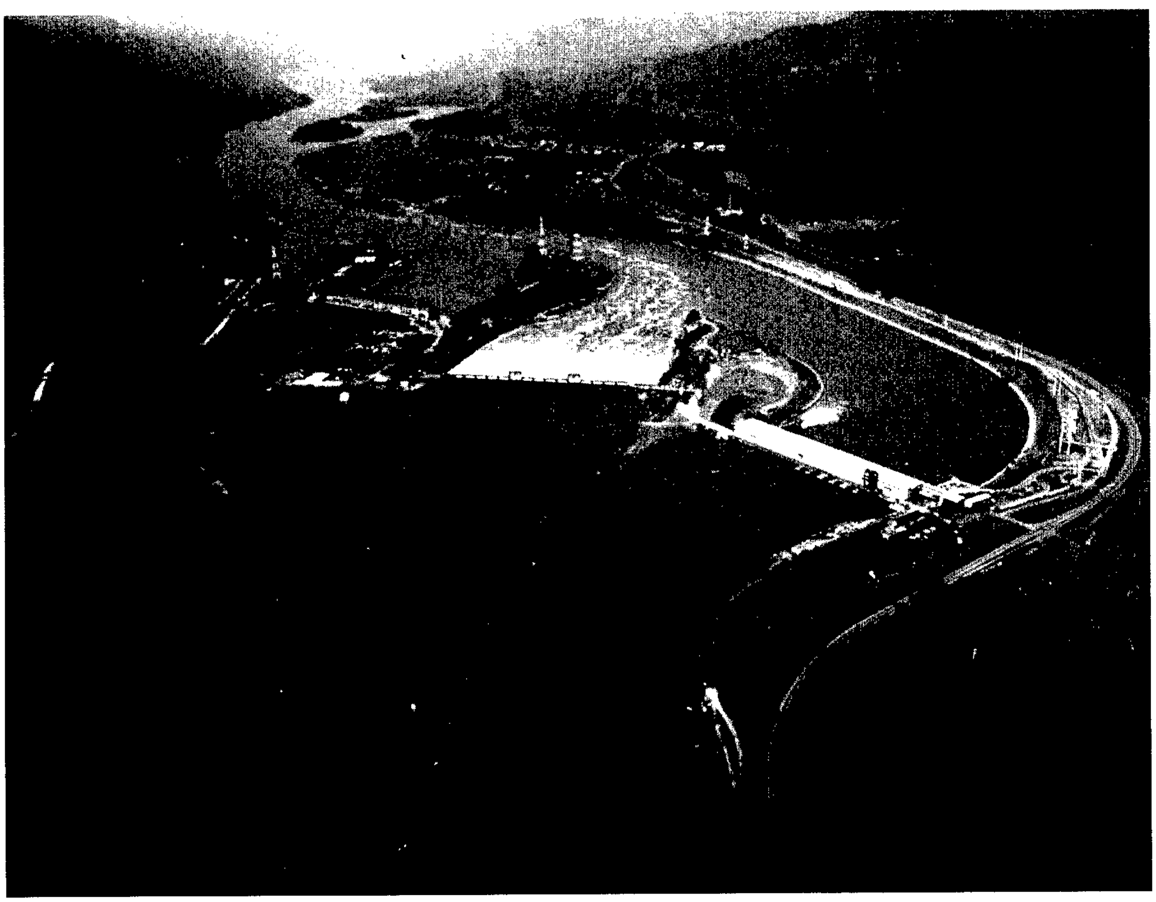
Experimental Hydroacoustic Deployments to Improve Estimates of Fish Guidance Efficiency

Michael E. Hanks and Gene R. Ploskey

August 2000



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Experimental Hydroacoustic Deployments to Improve Estimates of Fish Guidance Efficiency

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Preface

This report was prepared for the U.S. Army Engineer District, Portland, by the Fisheries Engineering Team, North Bonneville, WA. This team is part of the Water Quality and Contaminant Modeling Branch (WQCMB), Environmental Processes and Effects Division (EPED), Environmental Laboratory (EL), Vicksburg, MS, U.S. Army Engineer Research and Development Center (ERDC). Support for the effort was provided by the AScI Corporation, McLean, VA, Dyntel Corporation, Vicksburg, MS, and the Portland District. The research was conducted under the general supervision of Dr. Mark S. Dortch, Chief, WQCMB; Dr. Richard E. Price, Chief, EPED; and Dr. John W. Keeley, Acting Director, EL. Technical oversight was provided by Mr. Marvin Shutters of the Portland District.

Many other people made valuable contributions to this study. Mr. Gary Weeks, AScI, designed transducer deployments, installed hydroacoustic equipment, and acquired all data with occasional support from Dr. Larry R. Lawrence, EPED, Messrs. Peter B. Johnson and Mark Weiland of AScI Corporation, and Ms. Deborah S. Patterson and Mr. Mike Burczynski of DynTel Corporation. Mr. William T. Nagy with the Fisheries Field Unit, Portland District, provided programming support and data processing tools. Mr. Jason King, Ms. Gina George, and Ms. Athena Stillinger, EL contract students, also helped with deployments and data processing. Riggers from the Bonneville Project pulled trashracks whenever transducer deployments had to be changed or when equipment failed.

At the time of publication of this report, Dr. James R. Houston was Director of ERDC, and COL James S. Weller, EN, was Commander.

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1 Introduction

Background

Evaluation of efforts to meet the goal of maximizing the fish passage efficiency (FPE) for salmon smolts passing the Bonneville Project will require extensive research. Project FPE is the percentage of all smolts passing the dam by nonturbine routes; evaluation of FPE requires estimation of smolt passage through all significant routes. Estimations of FPE and evaluation of any enhancement by operational or structural changes are difficult because the Bonneville Project is among the most complex on the Columbia River. From the Oregon shore north towards Washington, the project is composed of a navigation lock, a 10-unit Powerhouse I, Bradford Island, an 18-gate spillway, Cascades Island, and an 8-unit Powerhouse II (Figure 1). Principal passage routes include the spillway and the two powerhouses. Within each powerhouse, passage can be

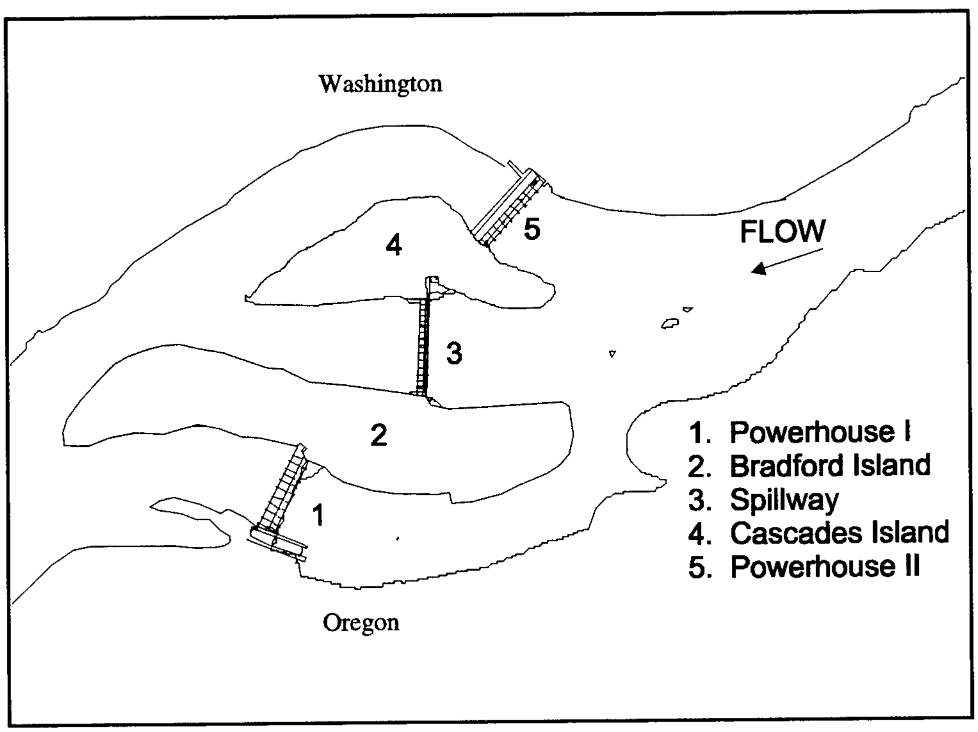


Figure 1. Aerial view of the Bonneville Project

through ice/trash sluiceways, turbines, or the juvenile bypass system (JBS). Smolts enter the JBS after they encounter submerged travelling screens (STS) in the upper part of the turbine intakes and are diverted to a bypass channel.

Fish guidance efficiency (FGE) is the percentage of the smolts that are diverted to the JBS from the turbine intakes. Estimates of FGE are important components of FPE, and it is essential that we have high levels of confidence in these estimates. Estimates of FGE at Bonneville Dam have been based mainly upon netting gate wells and turbine intakes (Gessel et al. 1989) and hydroacoustic sampling of intakes (e.g., Magne, Stansell, and Nagy 1989; Stansell et al. 1990; Ploskey et al. 1998). Fyke netting injures or kills fish and therefore is not a preferred method of sampling endangered fish stocks. Hydroacoustics can provide FGE estimates that compare favorably with those obtained from netting (Ploskey and Carlson 1999) and is a nonintrusive sampling method. The accuracy of hydroacoustic estimates of FGE can be limited, however, by the orientation and configuration of the sampling gear and by the spatial distribution of the juvenile salmon passing through turbine intakes.

Skalski et al. (1993) identified sampling error associated with spatial fish distribution as a major source of uncertainty associated with hydroacoustic monitoring at dams. Vertical distributions of smolts inside turbine intakes at Bonneville Dam have been shown to vary over time. The Fishery Field Unit of the U. S. Army Engineer District, Portland, sampled smolt distributions with up-looking transducers at several units of Powerhouse II in 1985 and of Powerhouse I in 1986 (Nagy and Magne 1986). Similar vertical distribution data were collected at the north end of Powerhouse I in 1995 with a deployment of down-looking transducers (Ploskey et al. 1998). These data clearly show a downward shift in the vertical distribution of fish at night compared to a shallower distribution during the day. This trend has implications for selecting transducer depths and for explaining day/night differences in FGE.

Available data also indicate that the horizontal distribution of smolt passage at Bonneville is not uniform. The focus of an analysis of horizontal fish distribution can vary from the trend in lateral distribution for an entire powerhouse, to differences between intakes for a single turbine unit, to variation within a single intake. Lateral distributions of smolts sampled at gate wells of Powerhouse I apparently are influenced by the number and location of operating units and sluice gates as well as the species of smolts (Willis and Uremovich 1981). Interactions among factors may account for a lack of consistency in other measurements of horizontal patterns of fish distribution (Uremovich et al. 1980; Willis and Uremovich 1981; Krcma et al. 1982). Hourly hydroacoustic sampling in front of intakes 8c-10b of Powerhouse I from 2200 through 0100 hours throughout June 1995 showed a distribution highly and consistently skewed toward Unit 10 (Ploskey et al. 1998). Units 3, 4, and 6 were inoperable at the time of that sampling. The spatial and temporal variations in fish distribution among turbines and the possibility of similar variation within turbines have great potential for creating bias in FGE estimates.

The difficulties presented by the nonuniform smolt distribution in obtaining an accurate FGE estimate at the powerhouses of the Bonneville Project are exacerbated by the size of the project. There are 18 turbine units at Bonneville,

with three intakes per turbine. Logistical considerations limit the numbers of transducers that can be deployed in a hydroacoustic evaluation of FGE at Bonneville. Therefore, spatial distribution data are essential for proper location of transducers. For hydroacoustics and other study methods that count fish, sample variance usually is highest where fish passage numbers are the greatest. In order to reduce sampling error, sampling effort must be high where variance is high (Skalski et al. 1996).

Measurement error associated with the selection and configuration of sampling equipment is another factor that affects the precision of hydroacoustic FGE estimates (Skalski et al. 1993). The physical structure that exists within the sample area may limit the use of certain beam widths and transducer orientations. Detectability characteristics of the target species, such as fish velocity, target size, and degree of schooling behavior, may dictate the use of certain transducer frequencies and ping rates. The presence of ambient noise, finally, can affect the selection of beam width, pulse length, and transducer frequency.

Purpose of This Study

Temporal and spatial variation of ambient noise and fish detectability may occur on fairly small scales. Fish detectability may decrease and ambient noise may increase, for example, with the increased water velocities and turbulence that may accompany high-flow events. Altering the sampling design of a study in response to changing conditions, however, may decrease the validity of spatial and temporal comparisons. Therefore, some degree of standardization of acoustic sampling methods is needed to assure not only that future acoustic studies will yield reliable data over a wide range of sampling conditions, but that these data can be compared among turbines and years. The objective of this study is to test transducer locations and orientations that may maximize the detectability of fish or at least to help identify important sampling considerations to increase the accuracy of estimates of fish passage and FGE.

2 Materials and Methods

Sampling Method

We deployed two split-beam and six single-beam transducers in several configurations in Intake 8b of Powerhouse I to assess the effects of transducer location and orientation on FGE estimates. All transducers were operating at 420 kHz with nominal beam widths of 7 deg. Sampling began on Julian date (JD) 110 (20 April 1997) and concluded on JD 210 (1 August 1997). Equipment failure or excessive noise during some tests limited the usefulness of some of the data collected during this period. For analysis, the remaining data were divided into four time blocks, which will be referred to as deployments in this report (Table 1).

Table 1
Julian Dates and Durations of Hydroacoustic Sampling Deployments from the Spring and Summer of 1997

Deployment	Julian Dates	Total Days
1	114-125	12
2	129-142	14
3	143-151	8
4	192-199	8

The single-beam transducers were always mounted in pairs. We mounted one pair of transducers 0.9 m from the Oregon side of the intake, another pair in the center of the intake, and the last pair 0.9 m from the Washington side of the intake. We mounted both of the split-beam transducers on the Oregon side of the intake (Figures 2-6).

We sampled all transducers at Intake 8b during each of the four deployment periods in 1997. In order to assess the effectiveness of different transducer configurations in detecting fish and estimating FGE, we changed the location and orientation of the single-beam transducers before each deployment. To provide a comparative reference for the changing positions of the single-beam transducers, we did not change the location and the orientation of the split-beam transducers during the study. The transducer deployments are described in the following section.

Deployments

Split-beams

To monitor the area below the STS for unguided fish, we attached one up-looking split-beam transducer 0.46 m from the Oregon side and 0.61 m above the bottom of Trashrack 1. This transducer was oriented into the intake opening at an angle 77 deg below horizontal and 11 deg toward the Washington side of the intake. We mounted the second split-beam transducer 0.46 m from the Oregon side and 0.61 m from the bottom of Trashrack 5. This down-looking transducer was aimed into the intake at an angle 53 deg above horizontal and 11 deg toward the Washington side of the intake (Figure 2). This allowed monitoring of the area above the STS for guided fish. The transducers were slow multiplexed at 2-sec intervals with a ping rate of 15 pings per second (pps) for 5 out of every 20 min.

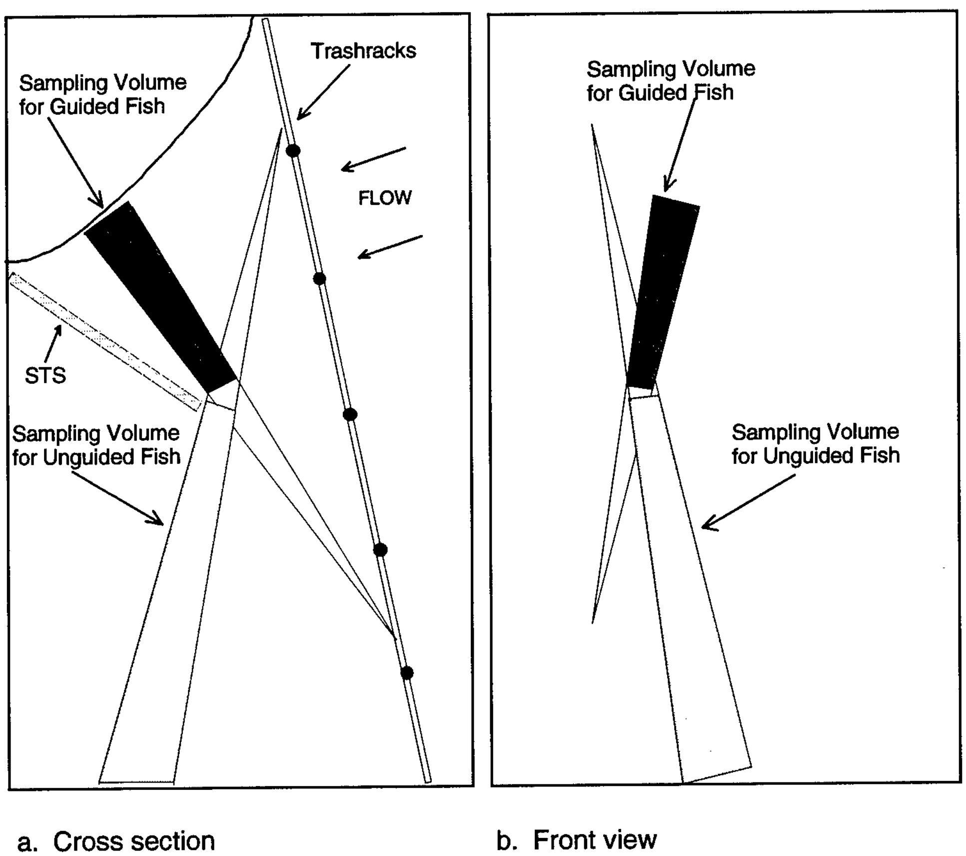
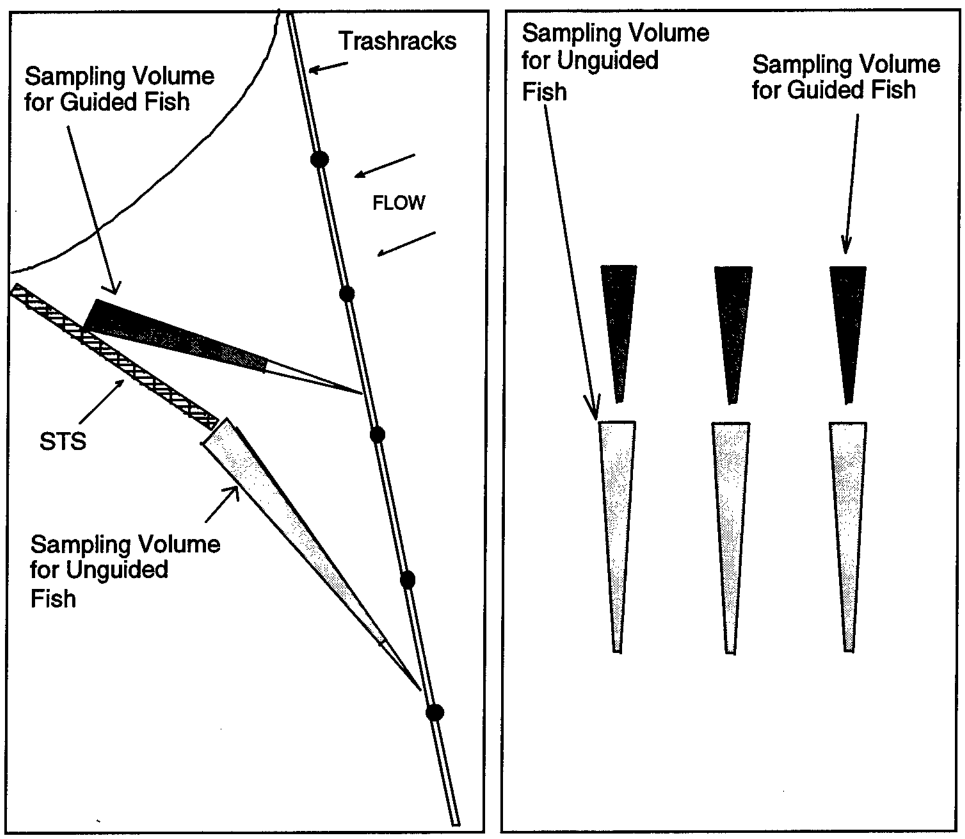


Figure 2. Cross section and front view of the split-beam transducer configuration during the spring and summer of 1997

Single-beam Deployment 1

In order to sample guided fish during the first deployment, we mounted three up-looking transducers 0.61 m from the bottom of Trashrack 3 and aimed them into the intake at an angle 17 deg above horizontal. In preliminary calculations of beam angle and location, we believed the distal end of the beam would be located at the confluence of the screen and the intake ceiling. For sampling unguided fish, we mounted three up-looking transducers 0.61 m from the bottom of Trashrack 5 and aimed them into the intake at an angle 51 deg above horizontal (Figure 3). Each pair of transducers was fast multiplexed at 30 pps for 5 out of every 20 min.



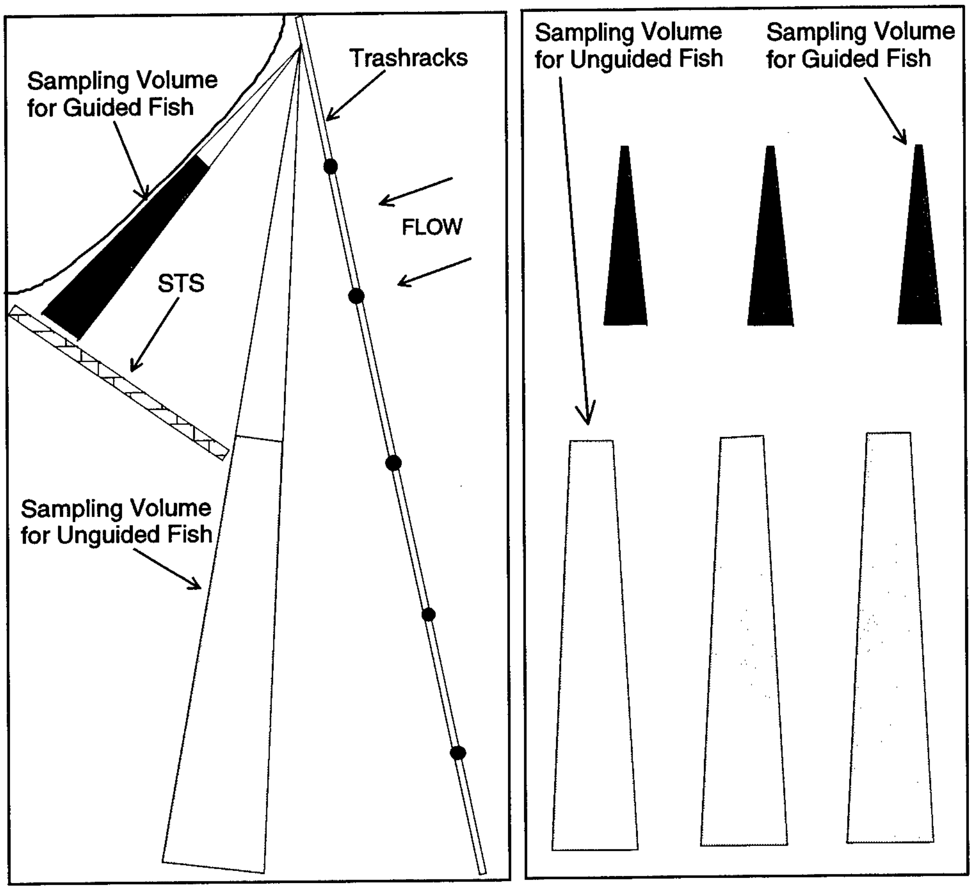
a. Cross section

b. Front view

Figure 3. Cross section and front view of the first deployment of the single-beam transducers during the spring of 1997

Single-beam Deployment 2

We mounted the transducers that sampled guided fish during the second deployment across the top of Trashrack 1 and aimed them into the intake at an angle 26 deg below horizontal. We mounted the transducers that sampled unguided fish across the top of Trashrack 1 and aimed them into the intake at an angle 83 deg below horizontal (Figure 4). Each pair of transducers was slow multiplexed at 15 pps for 5 out of every 20 min.



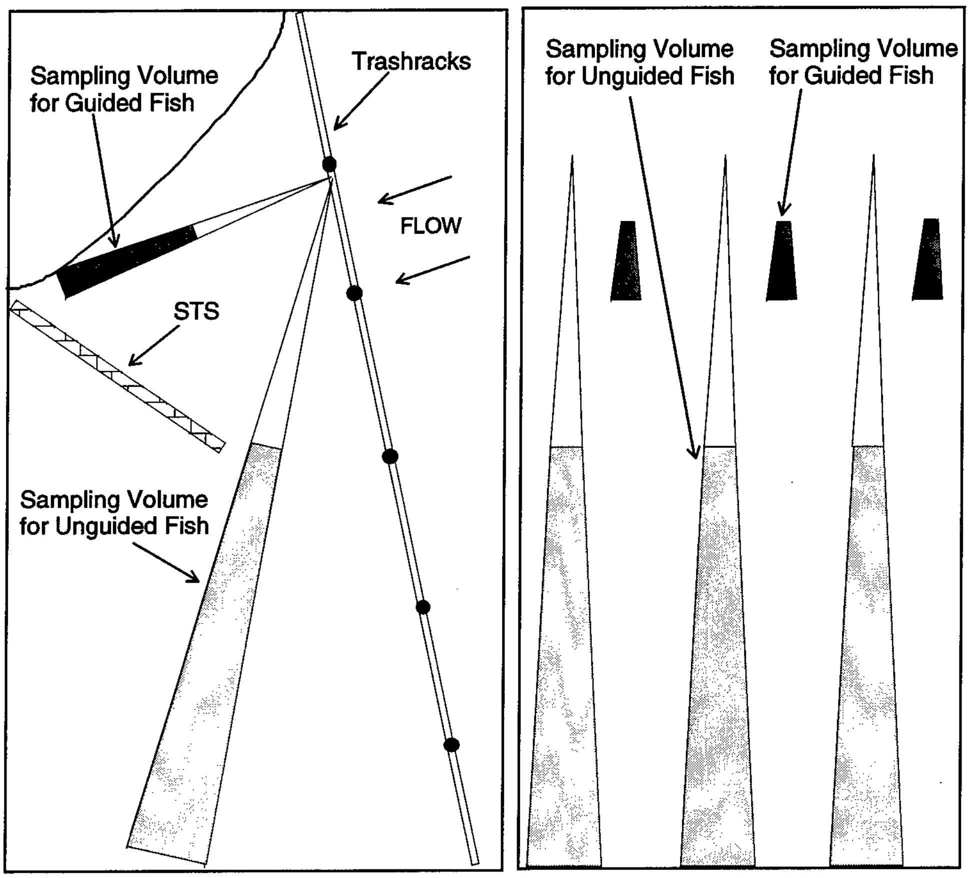
a. Cross section

b. Front view

Figure 4. Cross section and front view of the second deployment of the single-beam transducers during the spring of 1997

Single-beam Deployment 3

During Deployment 3, we mounted all single-beam transducers on the top of Trashrack 2 with every other one monitoring guided or unguided fish. We aimed the transducers that sampled guided fish into the intake at an angle 16 deg below horizontal. We aimed the transducers that sampled unguided fish into the intake at an angle 77 deg below horizontal (Figure 5). Each pair of single-beam transducers was slow multiplexed for 20 sec per transducer for 5 out of every 20 min, at a rate of 15 pps.

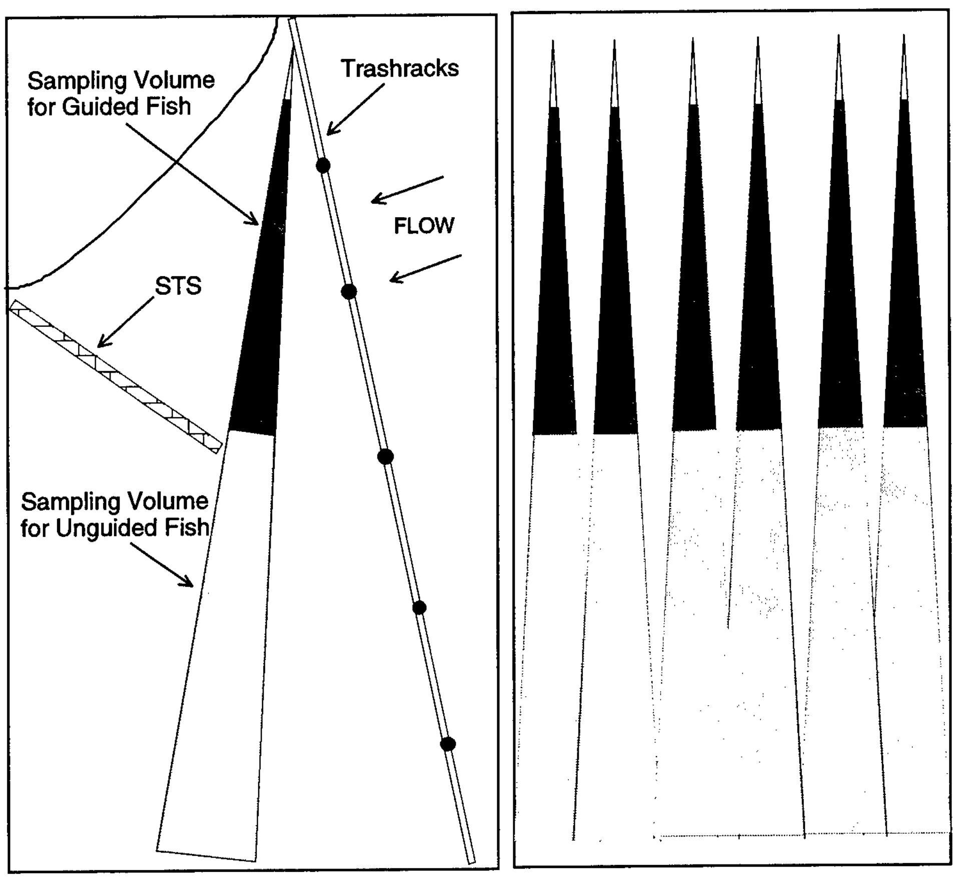


a. Cross section   b. Front view

Figure 5. Cross section and front view of the third deployment of the single-beam transducers during the spring of 1997

Single-beam Deployment 4

During Deployment 4, we mounted all single-beam transducers at the top of Trashrack 1 and aimed them into the intake at an angle 83 deg below horizontal (Figure 6). Guided and unguided fish were determined by range from the transducers. These transducers were slow multiplexed at 15 pps for 1 min per transducer for 14 out of every 20 min.



a. Cross section

b. Front view

Figure 6. Cross section and front view of the fourth deployment of the single-beam transducers during the summer of 1997

Calculations

We numerically expanded the count of every detected fish spatially by the ratio of the intake width to the diameter of the hydroacoustic beam at the range of detection:

$$ExpCount = \left[\frac{IW}{Mid\_R \times \tan\left(\frac{B\theta}{2}\right) \times 2} \right] \tag{1}$$

where

$ExpCount$	= expanded count
IW	= intake width, m
MID_R	= midpoint range of a trace, m
$B\theta$	= beam angle, deg

We then expanded acoustic counts temporally based on the fraction of an hour that the transducers sampled:

$$FinalCount = \left(\frac{T}{t}\right) \times ExpCount \tag{2}$$

where

$FinalCount$	= a spatially and temporally expanded number
T	= number of possible sampling intervals per hour
t	= number of intervals sampled

We estimated the FGE of Intake 8b as the number of guided fish divided by the sum of numbers of guided and unguided fish per sample period. We tested the difference in average daily FGE estimates between the two systems within each deployment with a t-test. We also used a t-test to test the difference in average daily FGE between the split-beam system and the different lateral positions of the single-beam system (Oregon side, middle, Washington side) during the third and fourth deployments.

We calculated the effective width of the hydroacoustic beams with a detectability model developed by BioSonics, Incorporated. Effective beam width was estimated from inputs of the nominal beam angle parallel and perpendicular to the direction of fish movement across the beam, fish velocity, pulse repetition rate, echoes required for detection, transducer orientation in deg from vertical, and fish trajectory angle (deg) from horizontal.

3 Results

During Deployment 2 (JD 129-142), entrained air along the ceiling of the turbine intake created excessive acoustic noise in the transducers used to sample guided fish. Therefore, we were unable to estimate FGE during this period, and these data were not analyzed.

Mean estimates of FGE from concurrently collected split-beam and single-beam data differed significantly during the first deployment but not during the third or fourth deployments (Figure 7). During Deployments 3 and 4, we obtained identical single-beam FGE estimates of 0.50, which were very similar to the associated split-beam FGE estimates of 0.46 and 0.45. During Deployment 1, however, we obtained an estimate of 0.30 from the single-beam transducers, which was significantly different from the associated split-beam estimate of 0.72 (Figure 7, Table 2).

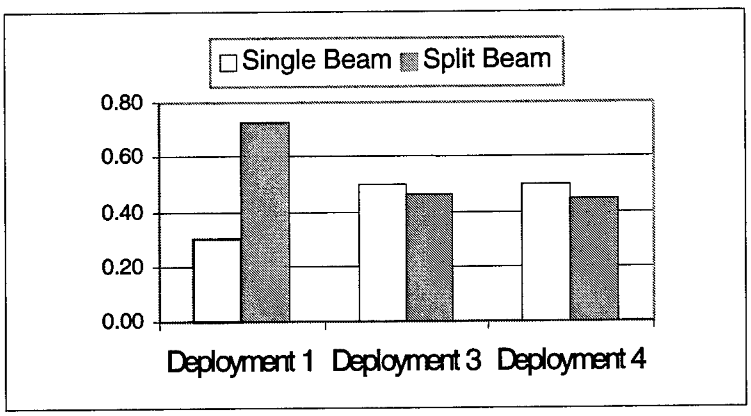


Figure 7. FGE for each deployment of the single-beam and the split-beam systems

Table 2
Mean Estimates of FGE among Split-beam and Single-beam Deployments with P Values from Two Sample Paired t-test Results

Deployment	N	Split-beam Mean FGE	Single-beam Mean FGE	P (Two-Tailed)
1	11	0.73	0.32	<<0.001
3	8	0.47	0.52	0.54
4	8	0.47	0.51	0.53

The horizontal distribution of fish was highly variable across the opening for Intake 8b during Deployment 1 (Figure 8). There were no clear trends in the numbers of fish detected daily either in the guided area of the intake (above the STS) or in the unguided area. Mean FGE did not differ significantly (P = 0.614) among sides of the intake for the first deployment (Figure 9).

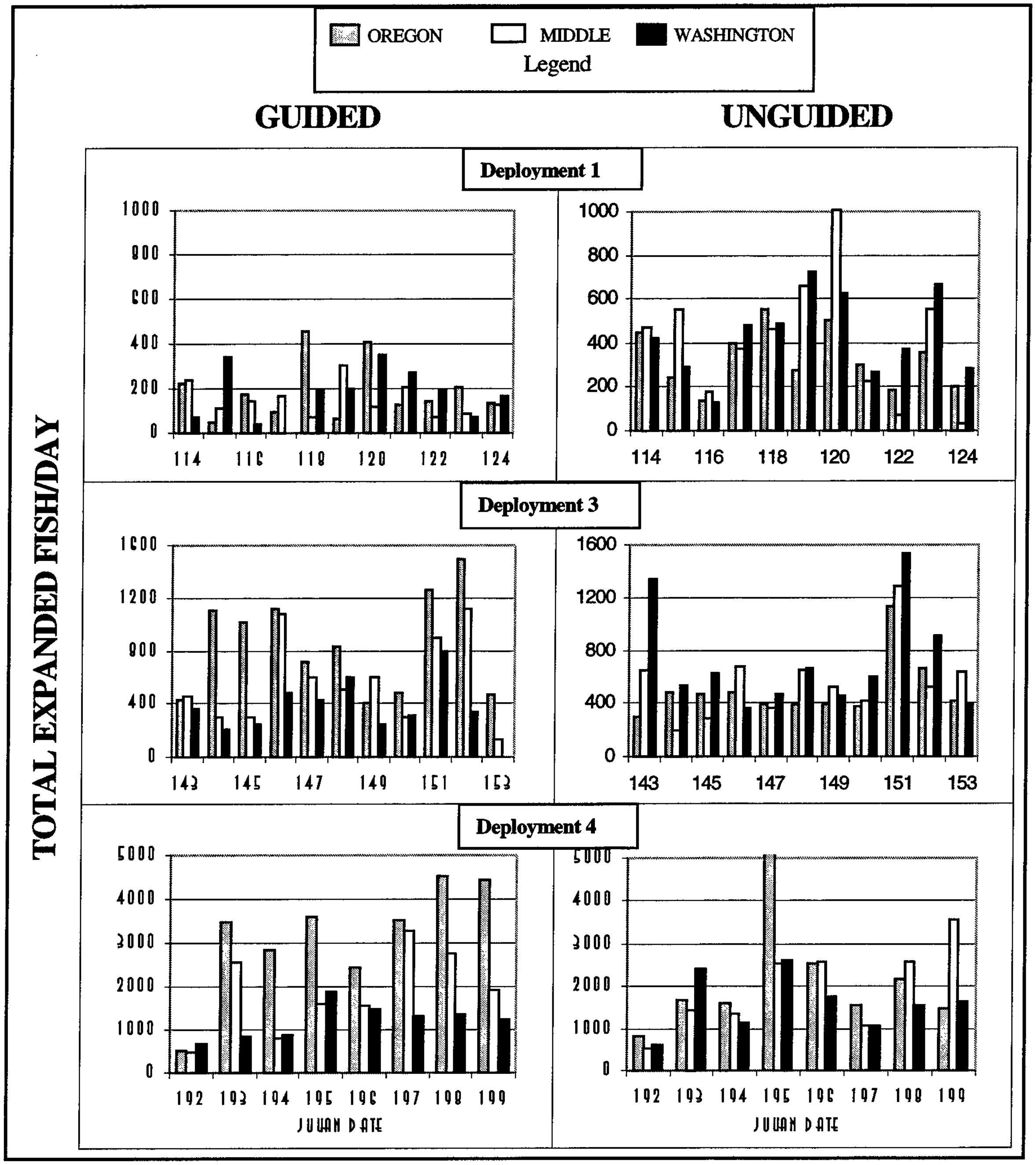


Figure 8. Horizontal distribution of fish across opening for Intake 8b as detected by the single-beam transducers. The intake was divided laterally into thirds: the Oregon side, the middle, and the Washington side.

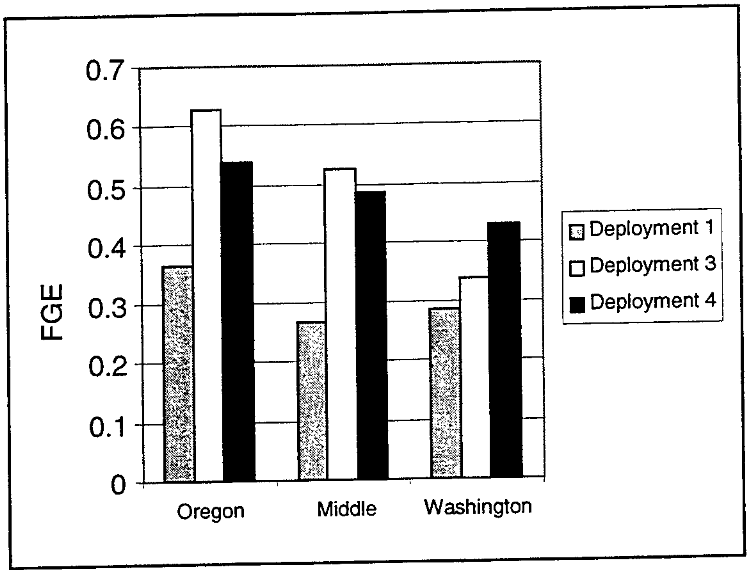


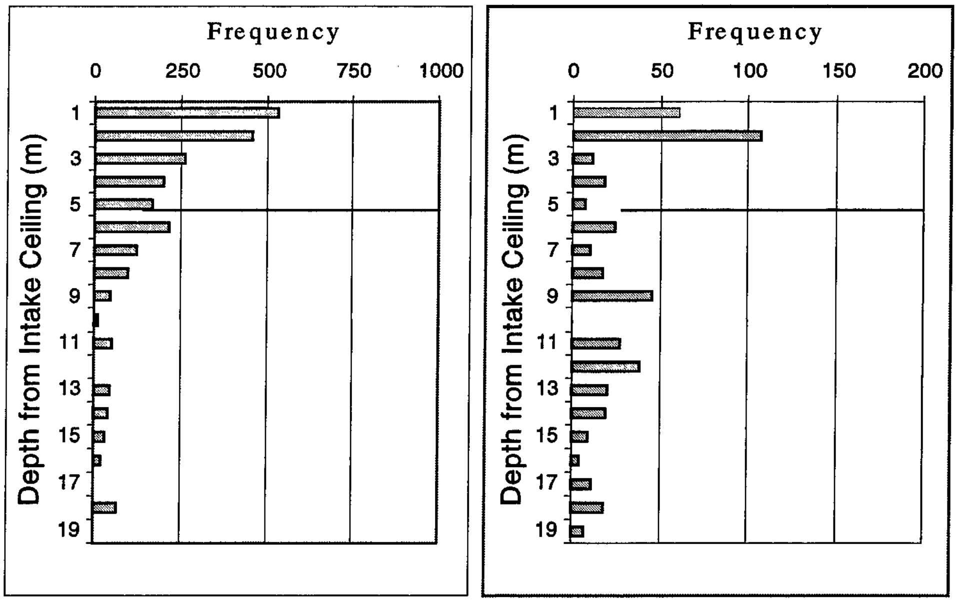
Figure 9. Horizontal distribution of mean FGE for each deployment as estimated from data collected by the single-beam transducers

In contrast to our findings from the first deployment, an examination of the horizontal distribution of fish indicates a nonuniform distribution of fish across the top portion of Intake 8b during the latter part of the season. During Deployments 3 and 4, single-beam transducers sampling above the STS detected significantly more guided fish on the Oregon side of the intake than in the middle or on the Washington side of the intake (Figure 8). There were no apparent lateral trends in the numbers of fish detected below the STS during sampling with Deployments 3 and 4. Estimates of FGE from the third and fourth deployments also reflect the skewed horizontal distribution for guided fish. The highest FGE occurred on the Oregon side of the intake and the lowest FGE occurred on the Washington side (Figure 9, Table 3).

Table 3
Mean Estimates of FGE Among the Split-beam System and the Lateral Position of the Single-beam System from the Third and Fourth Deployments, with P Values from Paired t-test Results.

Single-beam Lateral Position	N	Single-beam Mean FGE	Split-beam Mean FGE	P Two-Tail
Oregon Side	16	0.60	0.47	0.02
Middle	16	0.50	0.47	0.54
Washington Side	16	0.41	0.47	0.21

The vertical distribution of the smolts passing through the intake appeared to shift downward in the water column as the sampling season progressed (Figure 10). Split-beam data from the first deployment shows that the distribution was strongly skewed toward the top of the turbine intake. By the fourth



a. Deployment 1

b. Deployment 4

Figure 10. Vertical distribution of fish for Deployments 1 and 4 as detected by the split-beam transducers. The horizontal line indicates the depth of the lower edge of the submerged travelling screen

deployment, the distribution had clearly moved deeper, though there were still high numbers of fish passing at the very top of the intake.

Based upon inputs for detectability modeling (Table 4), model outputs indicated that the effective beam angle was close to the maximum (i.e., the nominal beam angle) for most ranges and deployments (Table 5). Effective beam widths at the minimum range sampled for the split-beam transducers and single-beam transducers used in Deployments 1 and 3 were > 6.1 deg. In Deployment 4, effective beam angles ranged from 0 deg at 1 m to 4.4 deg at 2 m, and they exceeded 6 deg at ranges > 3 m (Table 5)

Table 4
Detectability Modeling Inputs for Transducers Deployed at Bonneville Dam in 1997

Detectability Modeling Results	Split Beam		Deployment 1, Single Beam		Deployment 3, Single Beam		Deployment 4, Single Beam	
	Guided	Unguided	Guided	Unguided	Guided	Unguided	Guided	Unguided
Model Inputs								
Fish Velocity, m/sec (ft / sec)	0.9 (3)	1.7 (5.5)	0.9 (3)	1.2 (4)	0.9 (3)	1.4 (4.5)	0.9 (3)	1.4 (4.5)
Ping Rate, no. / sec	15	15	15	15	15	15	15	15
Minimum Number of Echoes for Detection	4	4	4	4	4	4	4	4
Beam Angle Along Direction of Travel	7	7	7	7	7	7	7	7
Beam Angle Perpendicular to Travel	7	7	7	7	7	7	7	7
Transducer Aiming Orientation	up	down	up	up	down	down	down	down
Orientation from Vertical	37	13	73	39	74	13	13	13
Angle of Fish Trajectory	30	30	25	25	25	20	25	20
Maximum Model Range, m (ft)	23 (75)	23 (75)	23 (75)	23 (75)	23 (75)	23 (75)	10 (33)	23 (75)

Table 5
Detectability Modeling Outputs for Transducers Deployed at Bonneville Dam in 1997

Split Beam				Deployment 1, Single Beam				Deployment 3, Single Beam				Deployment 4, Single Beam			
Guided		Unguided		Guided		Unguided		Guided		Unguided		Guided		Unguided	
Range m	Angle deg	Range m	Angle deg	Range m	Angle deg	Range m	Angle deg	Range m	Angle deg	Range m	Angle deg	Range m	Angle deg	Range m	Angle deg
0.7	0.0	2.5	0.0	0.2	0.0	1.2	0.0	0.2	0.0	2.3	0.0	1.0	0.0	2.3	0.0
0.9	3.7	2.7	1.5	0.5	5.6	1.4	3.7	0.5	5.1	2.5	0.4	1.6	1.5	2.5	0.4
1.2	5.1	3.0	3.0	0.7	6.4	1.6	4.8	0.7	6.2	2.7	2.8	1.7	2.8	2.7	2.8
1.4	5.8	3.2	3.8	0.9	6.7	1.8	5.4	0.9	6.6	3.0	3.7	1.8	3.5	3.0	3.7
1.6	6.1	3.4	4.4	1.2	6.8	2.1	5.8	1.2	6.7	3.2	4.3	1.9	4.0	3.2	4.3
1.8	6.3	3.7	4.8	1.4	6.9	2.3	6.0	1.4	6.8	3.4	4.8	2.0	4.4	3.4	4.8
2.1	6.5	3.9	5.1	1.6	6.9	2.5	6.2	1.6	6.9	3.7	5.1	2.1	4.7	3.7	5.1
2.3	6.6	4.1	5.3	1.8	6.9	2.7	6.3	1.8	6.9	3.9	5.3	2.2	4.9	3.9	5.3
2.5	6.7	4.4	5.5	2.1	6.9	3.0	6.4	2.1	6.9	4.1	5.6	2.3	5.1	4.1	5.6
2.7	6.7	4.6	5.7	2.3	7.0	3.2	6.5	2.3	6.9	4.4	5.7	2.4	5.3	4.4	5.7
3.0	6.8	4.8	5.8	2.5	7.0	3.4	6.6	2.5	7.0	4.6	5.9	2.5	5.5	4.6	5.9
3.2	6.8	5.0	5.9	2.7	7.0	3.7	6.6	2.7	7.0	4.8	6.0	2.6	5.6	4.8	6.0
3.4	6.8	5.3	6.0	3.0	7.0	3.9	6.7	3.0	7.0	5.0	6.1	2.7	5.7	5.0	6.1
3.7	6.8	5.5	6.1	3.2	7.0	4.1	6.7	3.2	7.0	5.3	6.2	2.8	5.8	5.3	6.2
3.9	6.9	5.7	6.2	3.4	7.0	4.4	6.7	3.4	7.0	5.5	6.2	2.9	5.9	5.5	6.2
4.1	6.9	5.9	6.3	3.7	7.0	4.6	6.8	3.7	7.0	5.7	6.3	3.0	6.0	5.7	6.3
4.4	6.9	6.2	6.3	3.9	7.0	4.8	6.8	3.9	7.0	5.9	6.3	3.1	6.0	5.9	6.3
4.6	6.9	6.4	6.4	4.1	7.0	5.0	6.8	4.1	7.0	6.2	6.4	3.2	6.1	6.2	6.4
4.8	6.9	6.6	6.4	4.4	7.0	5.3	6.8	4.4	7.0	6.4	6.4	3.3	6.2	6.4	6.4
5.0	6.9	6.9	6.5	4.6	7.0	5.5	6.8	4.6	7.0	6.6	6.5	3.4	6.2	6.6	6.5
5.3	6.9	7.1	6.5	4.8	7.0	5.7	6.9	4.8	7.0	6.9	6.5	3.5	6.3	6.9	6.5
5.5	6.9	7.3	6.5	5.0	7.0	5.9	6.9	5.0	7.0	7.1	6.6	3.6	6.3	7.1	6.6

(Sheet 1 of 3)

Table 5 (Continued)

Split Beam				Deployment 1, Single Beam				Deployment 3, Single Beam				Deployment 4, Single Beam			
Guided		Unguided		Guided		Unguided		Guided		Unguided		Guided		Unguided	
Range m	Angle deg	Range m	Angle deg	Range m	Angle deg	Range m	Angle deg	Range m	Angle deg	Range m	Angle deg	Range m	Angle deg	Range m	Angle deg
5.7	6.9	7.6	6.5	5.3	7.0	6.2	6.9	5.3	7.0	7.3	6.6	3.7	6.3	7.3	6.6
5.9	6.9	7.8	6.6	5.5	7.0	6.4	6.9	5.5	7.0	7.6	6.6	3.8	6.4	7.6	6.6
6.2	6.9	8.0	6.6	5.7	7.0	6.6	6.9	5.7	7.0	7.8	6.6	3.9	6.4	7.8	6.6
6.4	7.0	8.2	6.6	5.9	7.0	6.9	6.9	5.9	7.0	8.0	6.7	4.0	6.4	8.0	6.7
6.6	7.0	8.5	6.6	6.2	7.0	7.1	6.9	6.2	7.0	8.2	6.7	4.1	6.5	8.2	6.7
6.9	7.0	8.7	6.7	6.4	7.0	7.3	6.9	6.4	7.0	8.5	6.7	4.2	6.5	8.5	6.7
7.1	7.0	8.9	6.7	6.6	7.0	7.6	6.9	6.6	7.0	8.7	6.7	4.3	6.5	8.7	6.7
7.3	7.0	9.1	6.7	6.9	7.0	7.8	6.9	6.9	7.0	8.9	6.7	4.4	6.5	8.9	6.7
7.6	7.0	9.4	6.7	7.1	7.0	8.0	6.9	7.1	7.0	9.1	6.7	4.5	6.6	9.1	6.7
7.8	7.0	9.6	6.7	7.3	7.0	8.2	6.9	7.3	7.0	9.4	6.7	4.6	6.6	9.4	6.7
8.0	7.0	9.8	6.7	7.6	7.0	8.5	6.9	7.6	7.0	9.6	6.8	4.7	6.6	9.6	6.8
8.2	7.0	10.1	6.8	7.8	7.0	8.7	6.9	7.8	7.0	9.8	6.8	4.8	6.6	9.8	6.8
8.5	7.0	10.3	6.8	8.0	7.0	8.9	6.9	8.0	7.0	10.1	6.8	4.9	6.6	10.1	6.8
8.7	7.0	10.5	6.8	8.2	7.0	9.1	6.9	8.2	7.0	10.3	6.8	5.0	6.7	10.3	6.8
8.9	7.0	10.8	6.8	8.5	7.0	9.4	7.0	8.5	7.0	10.5	6.8	5.1	6.7	10.5	6.8
9.1	7.0	11.0	6.8	8.7	7.0	9.6	7.0	8.7	7.0	10.8	6.8	5.2	6.7	10.8	6.8
9.4	7.0	11.2	6.8	8.9	7.0	9.8	7.0	8.9	7.0	11.0	6.8	5.3	6.7	11.0	6.8
9.6	7.0	11.4	6.8	9.1	7.0	10.1	7.0	9.1	7.0	11.2	6.8	5.4	6.7	11.2	6.8
9.8	7.0	11.7	6.8	9.4	7.0	10.3	7.0	9.4	7.0	11.4	6.8	5.5	6.7	11.4	6.8
10.1	7.0	11.9	6.8	9.6	7.0	10.5	7.0	9.6	7.0	11.7	6.8	5.6	6.7	11.7	6.8
10.3	7.0	12.1	6.8	9.8	7.0	10.8	7.0	9.8	7.0	11.9	6.8	5.7	6.7	11.9	6.8
10.5	7.0	12.3	6.8	10.1	7.0	11.0	7.0	10.1	7.0	12.1	6.9	5.8	6.7	12.1	6.9
10.8	7.0	12.6	6.8	10.3	7.0	11.2	7.0	10.3	7.0	12.3	6.9	5.9	6.8	12.3	6.9

(Sheet 2 of 3)

Table 5 (Concluded)

Split Beam				Deployment 1, Single Beam				Deployment 3, Single Beam				Deployment 4, Single Beam			
Guided		Unguided		Guided		Unguided		Guided		Unguided		Guided		Unguided	
Range m	Angle deg	Range m	Angle deg	Range m	Angle deg	Range m	Angle deg	Range m	Angle deg	Range m	Angle deg	Range m	Angle deg	Range m	Angle deg
11.0	7.0	12.8	6.9	10.5	7.0	11.4	7.0	10.5	7.0	12.6	6.9	6.0	6.8	12.6	6.9
11.2	7.0	13.0	6.9	10.8	7.0	11.7	7.0	10.8	7.0	12.8	6.9	6.1	6.8	12.8	6.9
11.4	7.0	13.3	6.9	11.0	7.0	11.9	7.0	11.0	7.0	13.0	6.9	6.2	6.8	13.0	6.9
11.7	7.0	13.5	6.9	11.2	7.0	12.1	7.0	11.2	7.0	13.3	6.9	6.3	6.8	13.3	6.9
11.9	7.0	13.7	6.9	11.4	7.0	12.3	7.0	11.4	7.0	13.5	6.9	6.4	6.8	13.5	6.9
								11.7	7.0	13.7	6.9	6.6	6.8	13.7	6.9
								11.9	7.0	14.0	6.9	6.6	6.8	14.0	6.9
								12.1	7.0	14.2	6.9	6.7	6.8	14.2	6.9

Note: maximum ranges were truncated in most cases when the effective beam angle was approaching an asymptote. Underlined ranges and effective beam angles were the minima at which fish were counted.

(Sheet 3 of 3)

4 Discussion and Recommendations

Detectability modeling indicated that the sampling configurations used in this study produced effective beam widths that were close to the nominal beam width for most of our sampling ranges of interest (Tables 4 and 5). This means that the location and orientation of our transducers and the chosen ping rate combined to maximize the chances that a fish entering an acoustic beam would return ≥ 4 echoes and meet selection criteria. At any nominal beam angle, the number of echoes that a fish returns is dependent on the ping rate, duration of the fish in the beam, signal-to-noise considerations, and returned echo strength from individual pings relative to the threshold.

A high ping rate may provide large numbers of returned echoes from fish that pass through the acoustic beam. However, there must be sufficient time for sound to dissipate between pings, or echograms become saturated with noise due to sound reverberation in the confined spaces of a turbine intake. Therefore, the choice of ping rate is a trade-off between the number of echoes that a target returns and echogram clarity. For example, an exceedingly low ping rate may impair detectability by failing to return the minimum number of echoes, even though the echogram may be noise-free. In contrast, if the ping rate is too high, echo traces can be lost in background noise, and detectability declines. Our detectability model associates a higher ping rate with increased detectability, but does not account for the reduced detectability that noise reverberation may cause. The impact of noise reverberation on detectability must be evaluated on a site-by-site basis.

The detectability model that we used also associates beam orientation relative to fish movement with detectability. Using a beam orientation that approaches parallel to the average fish trajectory can maximize the amount of time a fish is in the beam and can increase detectability through a greater number of returned echoes. However, as the acoustic beam becomes more parallel to fish trajectory, less favorable fish aspect may cause fewer returned echoes to exceed the target strength threshold. Since smolt trajectories are often more horizontal than they are vertical, using a beam nearly parallel to fish trajectories also may limit the range of depths that can be sampled. This may introduce considerable bias into the data if vertical distributions are not uniform.

Locating the transducers as far away from the range of interest as the dimensions of the turbine intake will allow is a way of avoiding the possible limitations that unfavorable fish aspect and nonuniform vertical distribution can

cause while still increasing the time fish spend within the acoustic beam. This is usually accomplished by placing the transducers near the top or the bottom of the intake and aiming the beam close to vertical. With this configuration, most fish travel through the acoustic beam nearly perpendicular to the axis of the beam and are less likely to be oriented with their heads or their tails toward the transducer. This may result in less rejection of echoes due to insufficient echo strength. Also, fish at greater ranges from the transducer have longer distances to travel to get through the beam than fish near the transducer because the cross-sectional area of the acoustic beam increases geometrically as the sound waves travel. More time in the beam results in a larger number of returned echoes. In addition to maximizing the number of returned echoes, placing the transducer as far from the area of interest as possible enables more depth strata to be sampled than is possible when the transducers are oriented parallel to average fish trajectory. This helps to avoid bias related to inadequate sampling of nonuniform vertical distributions.

We found a highly significant difference in the FGE estimates from the two systems during the first deployment. FGE during Deployment 1 was estimated at 0.30 by the single-beam system and 0.72 by the split-beam system (Figure 7). The acoustic beams from the single-beam transducers that sampled above the bottom of the STS for guided fish were intended to contact the intake ceiling just above the STS. Close visual inspection of the transducer orientation, however, showed that these transducer beams contacted the screen before reaching the intake ceiling (Figure 3). As evidenced by the vertical distribution data obtained from the split-beam system, a large percentage of the guided fish passed very close to the ceiling of the intake during the first deployment (Figure 10). The up-looking, single-beam system in Deployment 1 failed to sample many guided fish that passed through the intake high in the water column because the transducer was not aimed accurately. Transducer aiming angles are determined from as-built drawings of intakes with fish screens and careful measurement of transducer location and nominal beam geometry. However, once the transducers are installed in the turbine and sampled, echograms provide little information about aiming angles or their appropriateness except for range to structure. The STS, which the single beams in Deployment 1 prematurely contacted, provided a consistent echo at a constant range much like one from the ceiling of the intake. The only difference between an echo from the screen as opposed to one from the ceiling would be 1-1.5 m of range, which can be easily overlooked in the haste to free up a crew of three to five riggers and a gantry crane. The error encountered in aiming single beams during Deployment 1 argues well for avoiding deployments that require sampling of areas near a structure unless they can be tested and revised to assure adequate detectability.

In contrast to the large differences in FGE estimation between the split-beam and single-beam data from Deployment 1, we obtained similar estimates from the two systems during the third deployment. Although the single-beam transducers that sampled guided fish during the third deployment did not appear to sample the bottom half of the STS (Figure 5), the FGE value of 0.50 was close to the associated split-beam FGE value of 0.45. The success was likely due in part to good detectability because of the orientation of the transducers that sampled guided fish. The beams were oriented very close to parallel to the trajectory of flow. In the high-velocity environment of a turbine intake, trajectories of small

fish usually are very similar to flow trajectories. This orientation maximized the duration of fish in the beam without adding excessive noise that was encountered in Deployment 2, where the beam was parallel to the ceiling. Detectability of the third single-beam deployment was not lower than the detectability of the split-beam deployment, as might have been expected if fish had been consistently oriented toward the sound source in head or tail aspect.

Estimates of FGE from the fourth deployment also were similar to those provided by the split-beam deployment despite less than optimal detectability by the single-beam transducers near the ceiling of the intake (Figure 6, Table 5). Given the narrow dimensions of the acoustic beam near the intake ceiling, it would appear that numbers of guided fish would be underestimated with this deployment. The FGE estimate of 0.50, however, was not significantly different from the estimate of 0.47 from the split-beam system (Table 2). An examination of the vertical distribution of fish detected by the split-beam system during this deployment shows that most guided fish passed close to the intake ceiling (Figure 10). However, these vertical distribution data were collected by the split-beam system from an area several feet further inside the intake than the area where the single-beam transducers sampled (Figures 2, 6). Flow lines in Figure 2 suggest that fish that enter the split beam near the intake ceiling would first pass through the single beams near the bottom of the first trashrack. At this range from the transducers, the single beams may have widened enough to enable adequate detectability. Despite apparent limitations, the fourth single-beam deployment provided similar FGE estimates to those of the split-beam deployment.

The FGE estimate from Deployment 4 was undoubtedly improved by the sample effort provided by six transducers. However, deployment of more than one or two transducers per intake is not cost-effective for normal hydroacoustic sampling. In the standardization workshop associated with this experimental sampling effort (Ploskey et al. 2000), Dr. John Skalski described advantages of sampling both guided and unguided fish with a single transducer beam. The advantage comes from simultaneous sampling of guided and unguided fish. The disadvantages stem from the inevitable differences in detectability resulting from beam geometry and target range from the transducer. The best alternative may be to sample guided and unguided fish with separate transducers aimed to maximize sample volumes in the respective ranges of interest and to fast multiplex the transducers to acquire simultaneous samples.

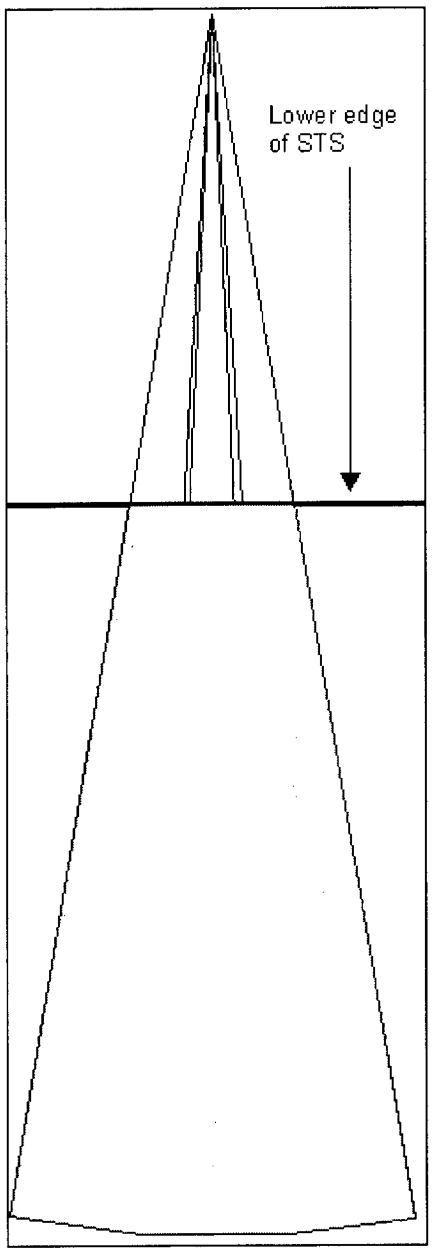
Changes in the vertical distribution of fish are thought to contribute to seasonal declines in FGE. FGE, as measured by our split-beam system, fell from 0.72 during the first deployment to 0.45 during the third deployment and 0.46 during the fourth deployment (Figure 6). Other researchers have noted seasonal declines in FGE at Bonneville Dam (e.g., Gessel et al. 1991; Stansell et al. 1990; Ploskey et al. 1998; Ploskey et al., in preparation). Gessel et el. (1991) reported a 30 percent drop in FGE for 0+ Chinook salmon *Oncorhynchus tshawytscha* from spring to summer during the years 1983-1989 at Bonneville. Since the individual transducer orientations were changed often during the 1997 field season, we cannot evaluate how well our single-beam deployments might have tracked seasonal changes in fish distribution and resulting FGE estimates.

The horizontal distribution of fish within the turbine opening was not uniform. Single-beam data from the third and fourth deployments indicate a skew toward the Oregon side of the intake for guided fish but no apparent pattern for unguided fish (Figure 8). As a result, FGE values were highest on the Oregon side of the intake, moderate in the middle, and lowest on the Washington side (Figure 9). Although the pair of split-beam transducers was mounted on the Oregon side of the intake, they were angled 11 deg laterally toward the Washington side and actually sampled near the center of the intake (Figure 2). This explains why the split-beam estimates of FGE from the third and fourth deployments were not different from the single-beam estimates from the middle and the Washington side of the intake, yet they were significantly different from the single-beam estimates from the Oregon side (Table 3). Although lateral comparisons of FGE matched well in this case, split-beam estimates of vertical distribution are questionable. Results of split-beam sampling in this study likely were confounded by variations in lateral distributions of fish passage with depth and slight (11-deg) but systematic differences in lateral position of the beam with depth. Since distributions of fish passage can be skewed laterally, it may be wise to aim the beams as close as possible to vertical so that each transducer samples only within a discrete lateral area.

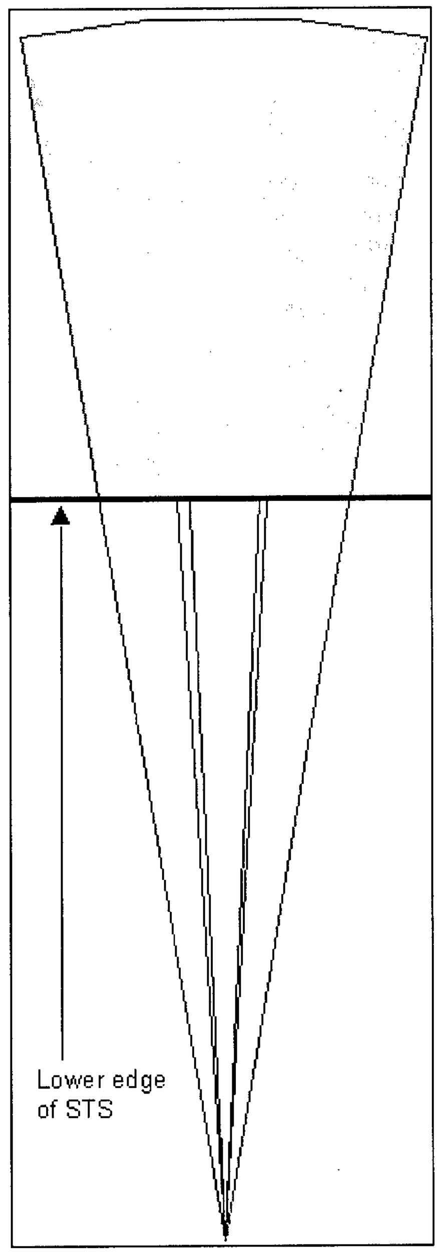
It is apparent that possible variation in the horizontal distribution of fish must be an important consideration in transducer deployments. Observed differences in FGE among pairs of transducers in single deployments ranged from about 8 percent (Deployment 1) to 29 percent (Deployment 3), so the effect of skewed lateral distributions is not necessarily trivial. The most suitable method for accounting for possible lateral variation of fish passage in intakes depends on the goal of the study. If the goal is to estimate FGE as accurately as possible at a few intakes, then the entire lateral range of each intake should probably be sampled with multiple pairs of transducers. However, if the goal is to estimate the FPE at a dam and many intakes will be sampled, monetary considerations and post-processing time constraints limit most studies to a single pair of transducers per intake. In this case, the most cost-effective way to ensure statistical validity is to randomly select the lateral area (Oregon side, middle, Washington side) to be sampled at each intake. The variability within the data will be accounted for over the temporal scale of the sampling season and over the spatial scale of an entire hydroelectric complex. Often, however, agencies request in-season FPE and FGE estimates for much smaller time periods and areas. The validity of such data may be questionable because randomly selecting the lateral location of the transducer can account only for the variation within the horizontal distribution of fish if many intakes are sampled over a sufficient length of time. Reducing the spatial or temporal dimensions of a study below the level that the original statistical design called for will affect the reliability of any conclusions that are drawn from the data.

In-season requests for passage data are often motivated by important dam operational considerations that may affect fish survival. For this reason, it has been proposed that researchers using hydroacoustics investigate sampling methods that can obtain valid passage estimates with subsamples of a season's data without increasing the costs or the data load to prohibitive levels. One suggested method involves mounting transducers on single-axis rotators. One transducer would be mounted in the center and near the top of an intake and

aimed down to sample unguided fish. Another transducer would be mounted in the center and near the bottom of the intake and aimed upward to sample guided fish (Figure 11). The rotators would be preprogrammed to change the aiming



a. Positions of acoustic beams for sampling unguided fish



b. Positions of acoustic beams for sampling guided fish

Figure 11. Front view of a hypothetical transducer deployment where the up- and down-looking transducers are each mounted on a single-axis rotator. Transducers sample each horizontal location for a predetermined length of time and are then rotated laterally to a new position

angle of the transducers and move the acoustic beam horizontally across the intake opening. This orientation would enable the entire vertical range of the intake to be sampled. In addition, the use of rotators would allow the sampling of a larger proportion of the lateral range of the intake than is possible with a pair of fixed transducers. This should decrease bias associated with variations in horizontal fish distribution enough to enable valid passage estimates with fairly small data sets and two transducers per sampled turbine intake.

Other options would be to develop simple multibeam transducers or electronic beam steering and eliminate the need for a rotator altogether. Both approaches would allow narrower beams and thereby improve signal-to-noise ratios for sampling. The replacement of single-beam transducers with multibeam or steerable beam transducers could be phased in over several years. This would seem to be a reasonable approach for reducing bias associated with skewed distributions. The assumption of a uniform lateral distribution of fish passage across intakes and spill bays was listed as a critical uncertainty of hydroacoustic sampling by experts attending the standardization workshop in 1997 (Ploskey et al. 2000).

A highly effective beam width from etectability modeling indicates that fish encountering the acoustic beam are likely to be detected; it does not necessarily mean that the transducer configuration enables a good estimate of FGE. The acoustic beam may be sampling effectively due to orientation and configuration of the transducers, but the opening of the intake may not be receiving unbiased coverage. For example, decreased sampling effectiveness near the ceiling of the intake introduced considerable bias into FGE estimates from the first deployment of the single-beam system. Also, the FGE estimates from the split-beam data from the third and fourth deployments may have been biased because of the location and orientation of the split-beam transducers. A conservative approach for future studies would be to sample the entire vertical range of the turbine intake; missing the area near the intake ceiling would be a crucial mistake if fish distributions are vertically skewed upward. Random selection of the horizontal position of the transducers for each intake would also reduce bias over the length of the field season. Ping rates should be high, and the transducers should be either located far enough away from the sample area or oriented in such a way that maximizes fish duration in the acoustic beam.

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13. ABSTRACT *(Maximum 200 words)*

This technical report describes results of studies conducted by the U.S. Army Engineer District, Portland, and the U.S. Army Engineer Research and Development Center to improve hydroacoustic estimates of fish guidance efficiency (FGE) in turbine intakes with fish guidance screens. The research was conducted at Turbine 8 at Powerhouse 1 of Bonneville Dam, Washington and Oregon. Estimates of FGE based upon multiple deployments of fixed-aspect hydroacoustic transducers were compared to assess the merits of the different sampling strategies.

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